

EXHIBIT 23

Controlling the 1 μm spontaneous emission in Er/Yb co-doped fiber amplifiers

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Abstract: In this paper we present our experimental studies on controlling the amplified spontaneous emission (ASE) from Yb^{3+} ions in Er/Yb co-doped fiber amplifiers. We propose a new method of controlling the Yb-ASE by stimulating a laser emission at 1064 nm in the amplifier, by providing a positive 1 μm signal feedback loop. The results are discussed and compared to a conventional amplifier setup without 1 μm ASE control and to an amplifier with auxiliary 1064 nm seeding. We have shown, that applying a 1064 nm signal loop in an Er/Yb amplifier can increase the output power at 1550 nm and provide stable operation without parasitic lasing at 1 μm .

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1. Introduction

High power sources operating in the 1550 nm region have experienced a growing interest in the past decade. Thanks to their eye-safety, they outperform the most popular Nd:YAG or

Yb: fiber lasers in many applications, like range finding [1], free space telecommunications [2], LIDAR systems and many others. The 1550 nm wavelength, placed in the middle of so called third telecommunication window, makes those sources also compatible with existing fiber telecom links. There are two main approaches to achieve 1550 nm radiation with good beam quality and relatively high output power. One can use a diode-pumped Er/Yb microchip laser, but the maximum power achieved in such constructions is strongly limited to hundreds of milliwatts by the glass damage threshold [3]. The second approach is to build a laser based on rare-earth doped fibers. Erbium fibers co-doped with Ytterbium make excellent active gain media to build medium/high power sources at the 1.5–1.6 μm region. Constructions using Er/Yb doped fibers in so called MOPA (Master Oscillator Power Amplifier) setup providing single-frequency and multiple-watt CW output were already shown in the literature [4–6]. Er/Yb doped LMA fibers also make excellent gain media for high-power fiber lasers [7,8]. In 2007 Jeong et al. presented a record-breaking setup, providing 297W of CW power from a large-core fiber laser [9]. Significant power scaling has been also achieved using only Er-doped, Yb-free LMA fibers. 88W of CW output power at 1590 nm was achieved using resonant pumping at 1532 nm [10]. Kuhn et al. presented an amplifier based on Er-doped LMA fiber with 67W output power at 1570 nm, pumped at 976 nm.

Co-doping of the erbium fiber with ytterbium allows to significantly increase the extractable output power of a fiber amplifier, but has also some critical drawbacks. Because of the energy transfer between Yb and Er ions, the actual efficiency of those amplifiers is limited to 25–30%, so the achieved output power will be always lower than in pure Yb^{3+} doped fibers. The main disadvantage of Er/Yb co-doped fibers is the unwanted amplified spontaneous emission (ASE) from the Yb^{3+} ions in the 1 μm band. It has been already shown, that the parasitic emission from excited Yb ions might be the main limitation factor in Er/Yb co-doped sources [4]. In the presence of relatively high pumping power, the Yb-ASE tends to transform into parasitic lasing, self-pulsing effects or even giant pulse formation, which may cause unstable operation of an amplifier at the nominal 1550 nm wavelength. In consequence, it can also lead to the active fiber damage.

A very elegant method of controlling the Yb-ASE emission by seeding an Er/Yb co-doped amplifier simultaneously by two signals: nominal 1550 and auxiliary 1064 nm was presented by Kuhn et al. [11]. It has been shown, that the presence of an additional 1064 nm signal has a good influence on the amplifier stability and allows to avoid spurious lasing effects. Further experimental investigation done by the same group showed, that the performance of Er/Yb co-doped amplifiers depends on the wavelength of the auxiliary 1 μm seed [12]. It was shown experimentally, that using a shorter wavelength seed, below 1064 nm, may increase the efficiency of the 1550 nm signal. The same issue was investigated numerically by Han et al. [13]. The predictions show, that introducing a co-pump-propagating 1 μm band signal, can effectively improve the available power of cladding-pumped Er/Yb co-doped fiber amplifiers.

In our work we present for the first time (to our knowledge) a new method of controlling the 1 μm emission in Er/Yb co-doped fiber amplifier by providing a positive feedback loop for the 1 μm signal in the amplifier. This loop forms a ring resonator inside an amplifier. The positive feedback induces stable and controllable lasing around 1060 nm, which has a good influence on the amplifier stability and efficiency at 1550 nm. In our work we have compared our method to the method presented in [11], based on amplifier seeding with an auxiliary signal at 1064 nm. In addition, we have modified the setup presented in Ref. [11]. by launching the 1064 nm seed not only co-directionally to the 1550 nm signal, but also in counter-direction. In this paper, experimental results obtained using both methods were compared and discussed.

2. Amplifier design

Our all-in-fiber MOPA setup used in our experiments is shown in Fig. 1. It consists of two amplifying stages. The first stage (pre-amplifier) is an erbium doped fiber amplifier (EDFA) based on 1.1m long highly erbium-doped fiber (Liekki Er80) pumped bidirectionally by two 650 mW 980 nm single-mode pumps. It amplifies the seed signal to about 270 mW with a

very satisfactory noise figure (NF) of 4.5 dB. The second stage (power amplifier, EYDFA) is based on 6m long Erbium/Ytterbium doped double-clad fiber with 6 μm core and 125 μm cladding diameter (Nufern SM-EYDF-6/125-HE). It is backward-pumped by two 975 nm 10W laser diodes coupled with the double-clad fiber by a pump combiner. The unabsorbed pump light from the second stage is rejected by a cladding-mode stripper, which is a fiber splice placed in high refractive index adhesive, so the unabsorbed pump is radiated out from the fiber. Both stages are separated with an isolator which protects the first stage from back-scattered light and allows to avoid unwanted lasing in the amplifier. On both sides of the power amplifier 1064/1550 WDM couplers were inserted, to reject and monitor the forward and backward propagating Yb-ASE. The amplifier is seeded by a 1 mW DFB laser diode. To avoid unwanted back-reflections we have used fiber isolators at both 1064 nm outputs and in the 1550 nm signal output. Additionally, all fiber ends were terminated with angled FC/APC connectors.

The amplifier performance without any additional 1064 nm signal and the recorded 1550 nm signal optical spectrum are shown in Fig. 2. It can be clearly seen, that in the presence of pumping power above 10W, the Yb-ASE is starting to grow rapidly, limiting the available

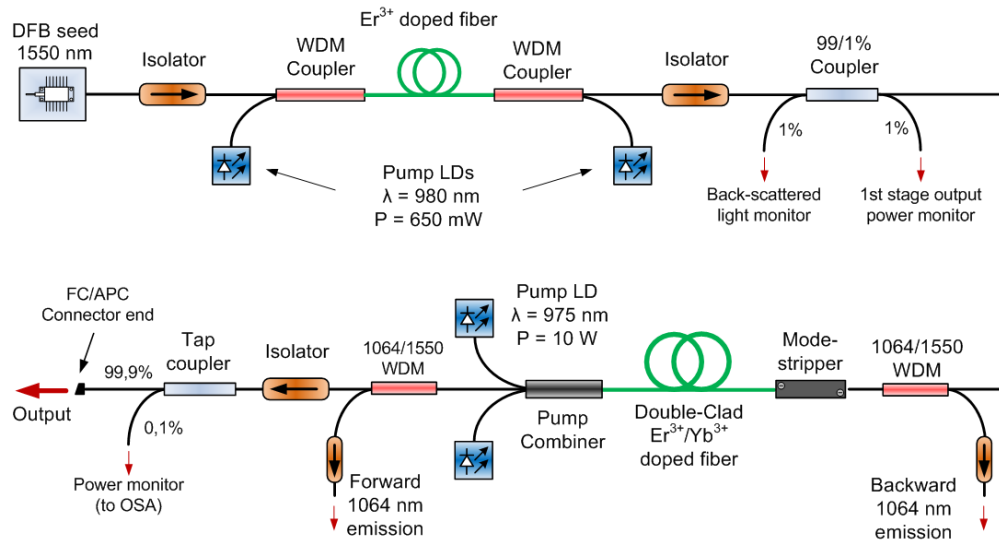


Fig. 1. All-in-fiber MOPA setup.

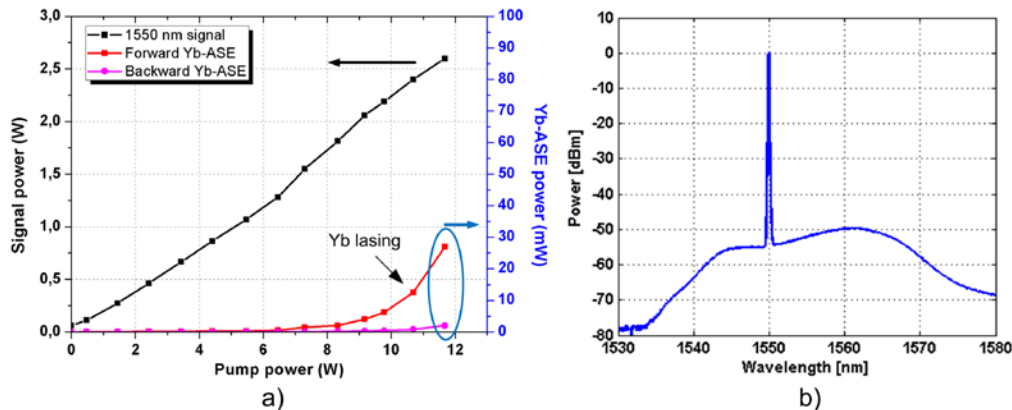


Fig. 2. (a) Amplifier performance and (b) output signal spectrum recorded with 0.2 nm resolution.

1550 nm output power. To avoid the consequences of self-pulsing, we have limited the pumping power in this measurement to 12W.

The backward Yb-ASE level is significantly lower than the forward ASE, which agrees with the observations done by Han et al. [13]. The maximum amplifier output power at 1550 nm was 2.6W with 12W pumping, although the parasitic lasing at 1 μm starts already at around 11W of pumping. The recorded forward and backward Yb-ASE spectra for different pumping levels are shown in Fig. 3. In both cases a strong peak around 1064 nm can be seen. This lasing had a tendency to be unstable—the spectrum shape was changing in time, and also the Yb-emission power was strongly fluctuating (between 25 and 35 mW at 12W pumping).

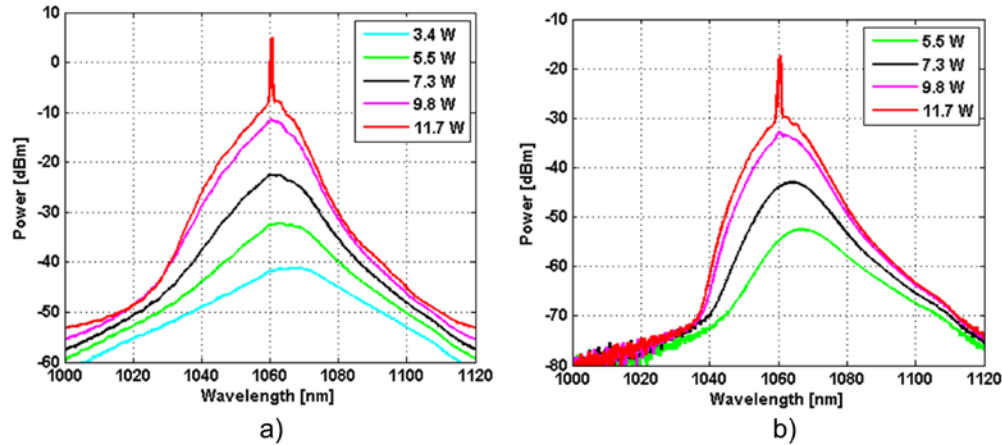


Fig. 3. Recorded (a) forward and (b) backward Yb-ASE spectra with parasitic lasing.

As the results show, the Yb-lasing threshold is relatively low. This agrees with the results showed by Kuhn et al. in Ref. [11], where the Yb-lasing occurred at around 7-8W of pumping. During our experiments, the active fiber was damaged twice due to the parasitic Yb-lasing and self-pulsing effects. This demonstrates, that suppressing of the Yb-ASE is necessary in order to build power scalable and reliable Er/Yb sources.

3. Experiments and results

Firstly, we have investigated the possibilities of controlling the Yb-ASE by seeding the amplifier with an additional 1064 nm signal. As mentioned in the introduction, we have made a modification to the method presented in [11], by introducing the 1064 nm signal not only co-directional to the 1550 nm signal, but also in the counter-propagating scheme. Both setups are shown in Fig. 4.

In both cases, the EDFA and EYDFA designs are the same as described in the previous section. The additional 1 μm signal is provided by a 40 mW semiconductor laser diode (QPhotonics) with <0.01 nm spectral width. The signal is amplified in an ytterbium-doped fiber amplifier (YDFA) to the maximum value of 300 mW, to balance the power of both input signals.

The output power vs. launched pump power characteristics in the co-directional scheme are shown in Fig. 5. In order to investigate the dependence of the amplifier performance on the auxiliary signal power, the measurements were done for three different YDFA power levels (40, 200 and 300 mW).

In all cases the maximum 1550 nm power does not exceed 2.5W and is about 4% lower than without any 1064 nm signal. Although, the presence of 1064 nm seed prevents from parasitic lasing and provides stable amplifier operation. The 1064 nm output power for 40, 200 and 300 mW input was measured to be 260, 310 and 320 mW, respectively. The 1064 nm signal output spectra are shown in Fig. 6. They all have comparable shapes and the SNR ratio

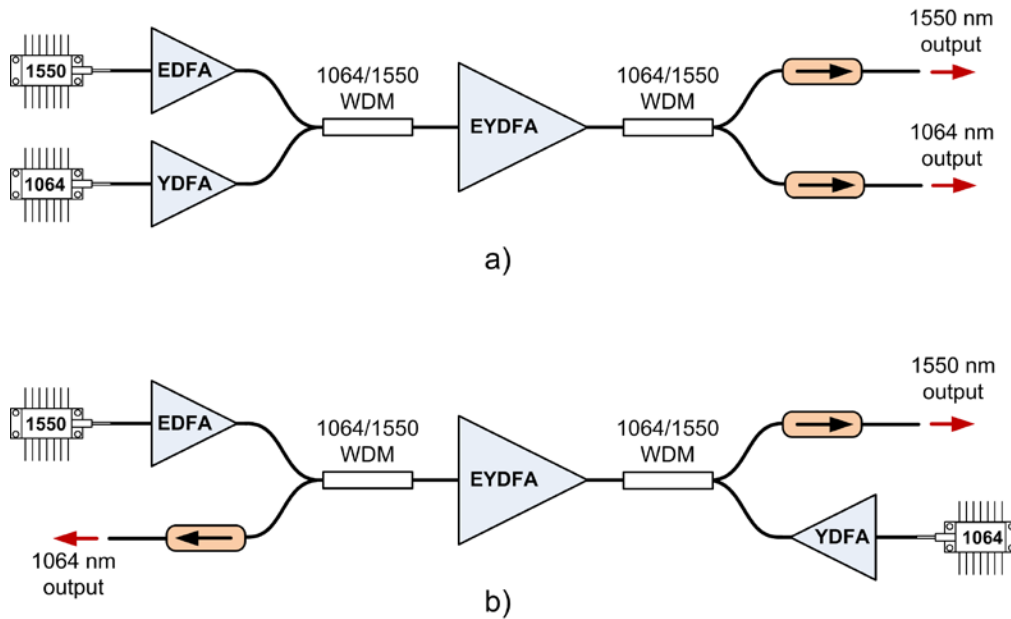


Fig. 4. Amplifier setups with additional seed signal in (a) co-directional and (b) counter-propagating scheme.

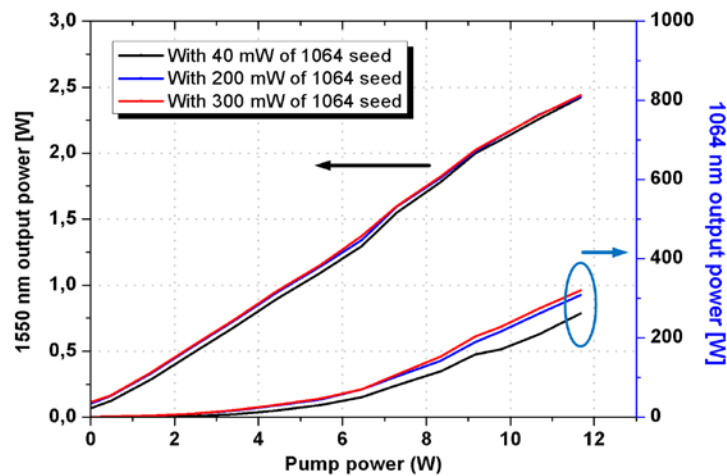


Fig. 5. Amplifier performance with additional co-directional 1064 nm seed

at the level of 40 dB in all three cases. A stable amplification process can be seen, without any unwanted lasing effects, which makes the 1550 nm amplification safe without any self-pulsing risk.

A slightly different behavior of the Er/Yb amplifier can be observed when the additional 1064 nm seed is launched counter-directionally to the 1550 nm signal or, in other words—co-directional to the pump (setup shown in Fig. 4b). The measurements show, that in such arrangement the 1550 nm efficiency can be slightly improved or, in the worst case, be equal as without any auxiliary seed. This is due to the reabsorption effect in the active fiber. The auxiliary Yb-band signal acts as an additional pump for the Er-band signal. This effect has been discussed in [13] and also verified experimentally by Kuhn et al. [12]. The output power

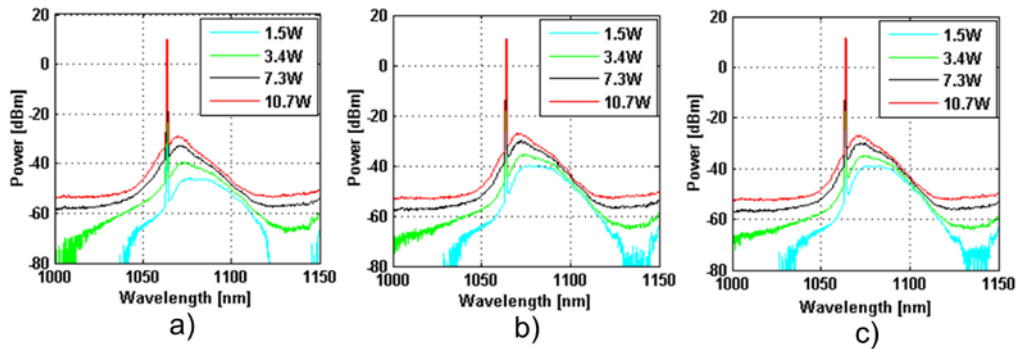


Fig. 6. Co-directional Yb-signal spectra for different 1064 nm input signals: (a) 40 mW, (b) 200 mW, and (c) 300 mW measured with 0.1 nm resolution.

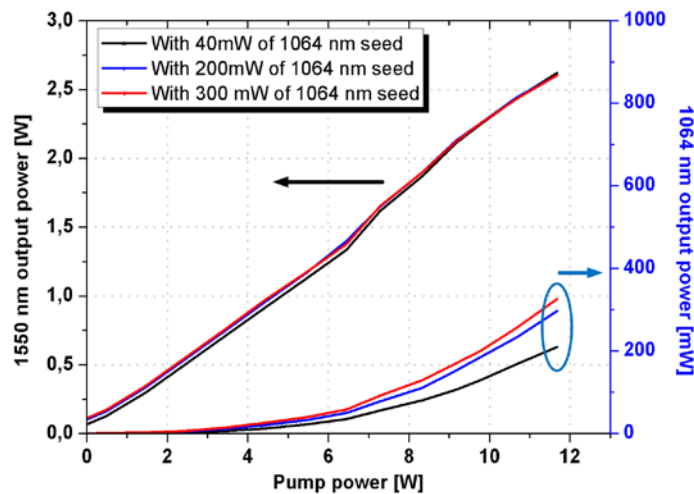


Fig. 7. Amplifier performance with additional counter-directional 1064 nm seed

vs. launched pump power characteristics in the counter-directional scheme are shown in Fig. 7. Again, the input power of the 1064 nm seed has almost no influence on the 1550 nm output power level, which agrees with [11]. The maximum power of 2.62W was achieved with 40 mW of Yb-signal.

The 1064 nm output power for 40, 200 and 300 mW input was measured to be 210, 300 and 330 mW, respectively. Again, as in the co-directional scheme, the 1064 nm signal seems to be well amplified without any parasitic lasing, providing stable and damage-free amplifier operation. The recorded Yb-signal spectra for different YDFA power levels are shown in Fig. 8. The SNR ratio is at the level of 40 dB in all three cases.

Our results agree with those presented by Kuhn et al. [11,12], that additional 1064 nm seeding is an effective method of suppressing spurious lasing from Yb ions and increases the power scalability of Er/Yb co-doped amplifiers. Moreover, launching the auxiliary signal co-directionally to the pump (counter-directionally to the 1550 nm seed in our setup) increases the 1550 nm signal efficiency and gives, in general, better performance as the co-directional scheme, which also agrees with the theoretical predictions presented by Han et al. [13]. Although, this method has one important drawback—it requires usage of an additional seed laser (e.g. DFB laser diode) and, not necessarily, an ytterbium-doped fiber amplifier. Thus, the complexity and costs of the whole system will be significantly increased. To overcome this issue, we propose a new method of controlling the Yb emission, by utilizing the Yb-ASE

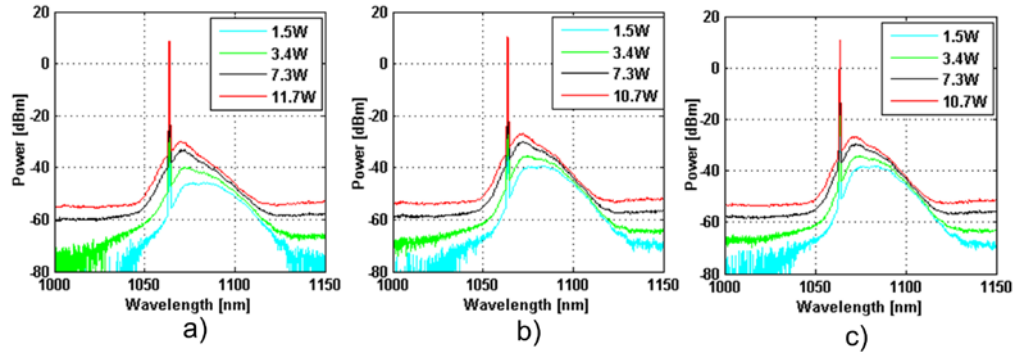


Fig. 8. Counter-directional Yb-signal spectra for different 1064 nm input signals: (a) 40 mW (b) 200 mW, and (c) 300 mW measured with 0.1 nm resolution.

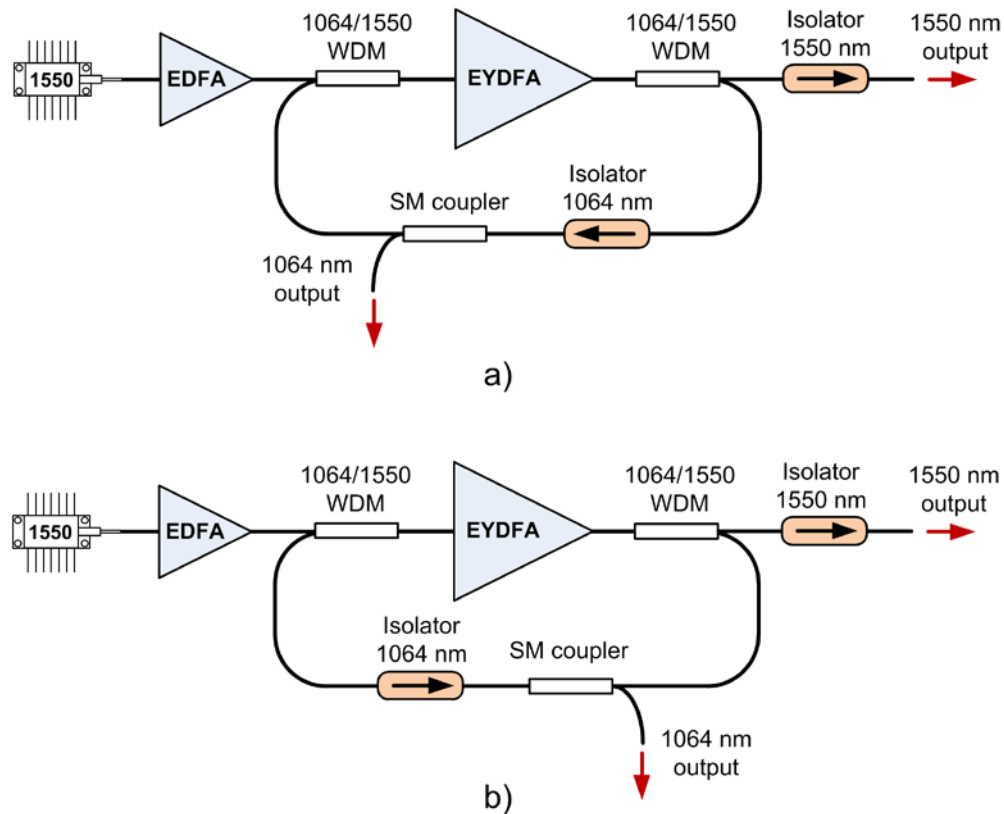


Fig. 9. Er/Yb fiber amplifier with stimulated laser emission at 1 μ m wavelength. Setup with (a) co-directional and (b) counter-directional 1 μ m signal.

generated in the amplifier and induce stimulated lasing at 1 μ m. This can be done by providing a positive feedback loop for the 1 μ m signal. In other words, we apply a ring laser resonator for the 1 μ m wavelength inside the 1.55 μ m amplifier. The direction of the signal circulation can be determined by applying a fiber isolator in the loop, as in conventional fiber ring lasers. Hereby, both co-directional (Fig. 9a) and counter-directional (Fig. 9b) 1064 nm propagation can be achieved.

To monitor the stimulated 1 μ m lasing, a single-mode fiber coupler was placed inside the loop. The amplifier performance was investigated for three couplers with different coupling

ratios: 3 dB (50/50), 10 dB (90/10) and 20 dB (99/1). The measured output power vs. launched pump power characteristics are plotted in Fig. 10. The maximum 1550 nm output power of 2.67W was achieved by using a backward-propagating signal in the fiber loop with 99/1 coupling ratio (red curve on Fig. 10). It means, that the efficiency has improved by about 3%, compared to a conventional setup without any feedback or auxiliary seed signal. In this configuration also the output 1064 nm power was the smallest of all. The worst performance was obtained by using a feedback loop with co-directional signal and 50/50 coupler (output power at the level of 2.325W, black curve on Fig. 10). In general, the counter-propagating scheme again appears to be more efficient than the co-propagating setup due the reabsorption effect, which is noticeable when the Yb-band signal is launched in the co-pump direction [13]. Similar behavior could be observed in the amplifier configuration with auxiliary 1064 nm seed [12].

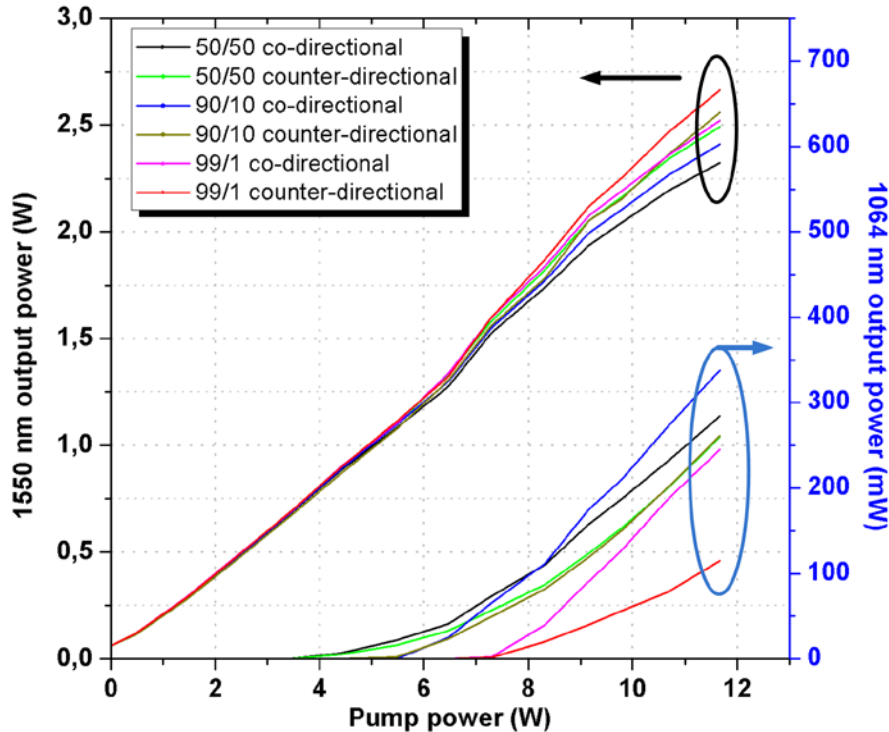


Fig. 10. Output power of the Er/Yb fiber amplifier with stimulated lasing at 1 μm .

Based on the output power characteristics shown in Fig. 10 we can assume, that in all cases the Yb-signal starts lasing with pump powers around 7-8W. To confirm it, we have measured the Yb-signal spectra in the presence of five different pumping power levels. The results are shown on the 3D plots in Fig. 11. It can be clearly seen, that the lasing threshold moves towards higher pumping level, when a coupler with stronger directivity is used. For example, with 50/50 coupler the Yb lasing starts at around 7W, compared to 9W needed with the 99/1 coupler. The maximum 1064 nm signal power was achieved with 90/10 coupling (in both counter-directional and co-directional setups). 90/10 seems to be the optimal coupling ratio for the 1064 nm resonator, balancing the unsaturated gain and cavity losses. It is worth mentioning, that in all cases the Yb-lasing was very stable at the maximum pumping power. No output power fluctuations were observed.

In order to check the stability of the amplifier with stimulated 1064 nm lasing, we have performed a long-term measurement. Two parameters were monitored: the Yb-signal optical spectrum shape and the 1550 nm output power. Both tests were done in the counter-

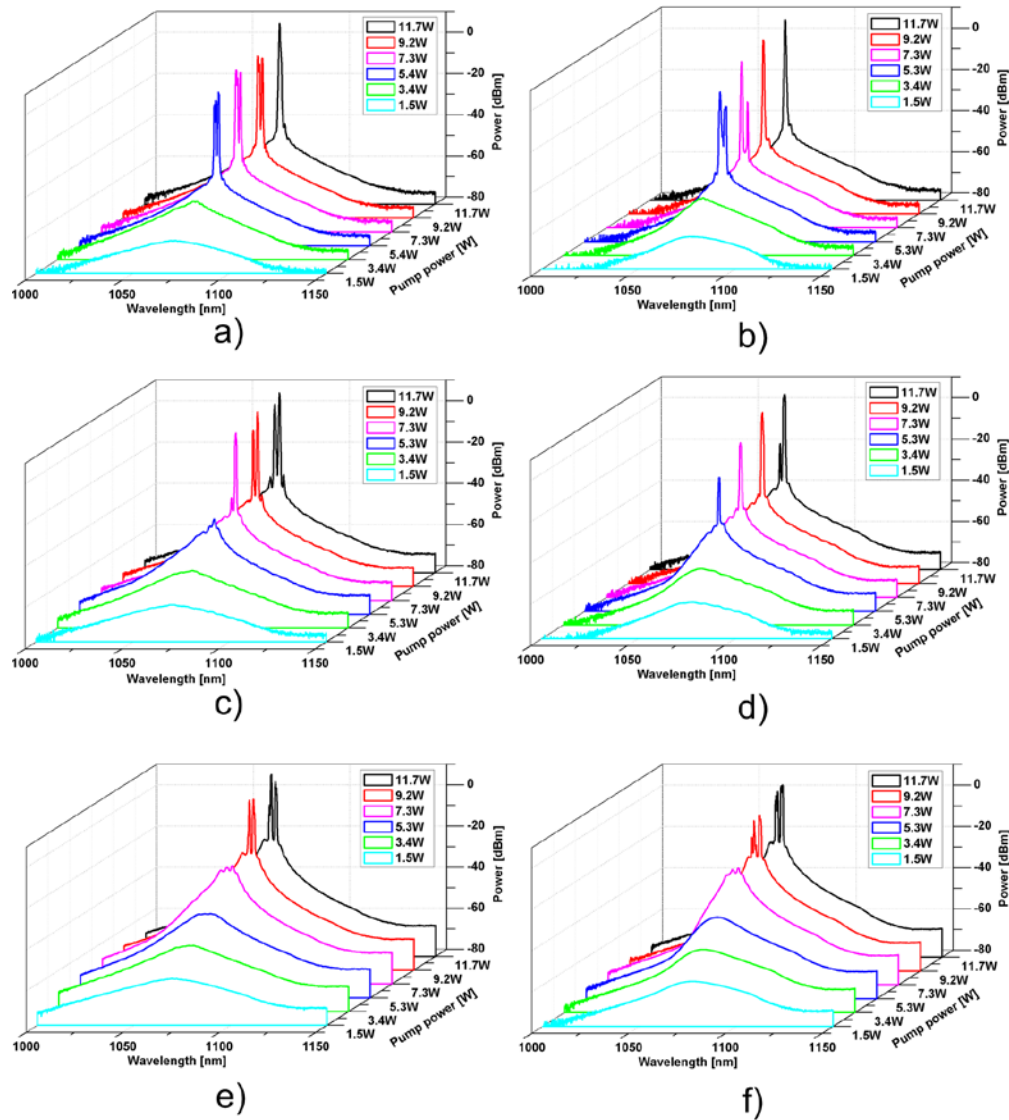


Fig. 11. Recorded Yb-signal spectra. (a) Co-directional 50/50 coupler, (b) counter-directional 50/50 coupler, (c) co-directional 90/10 coupler, (d) counter-directional 90/10 coupler, (e) co-directional 99/1 coupler, (f) counter-directional 99/1 coupler.

directional setup (as in Fig. 9b), with the 90/10 coupler and 12W pumping. The results of the long-term measurement are shown in Fig. 12. The shape of the Yb-signal spectrum is stable and does not change in time. Also the power fluctuations of the output 1550 nm are negligibly small.

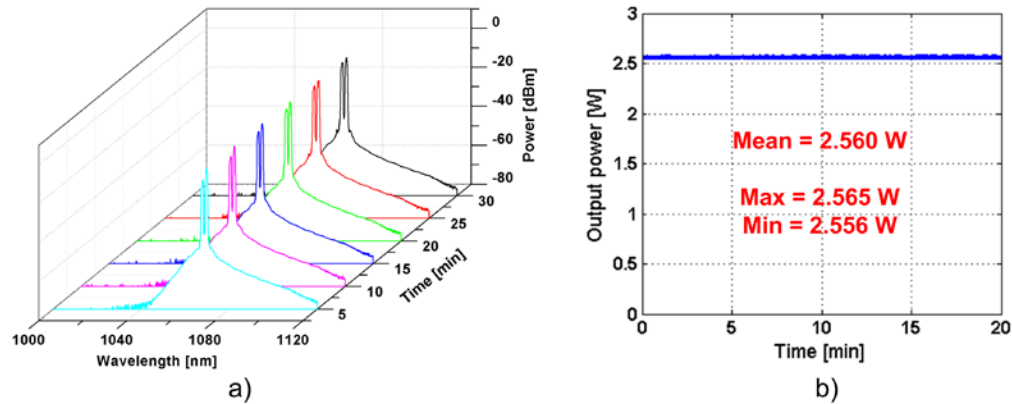


Fig. 12. Long-term stability test results. (a) Yb-signal spectra and (b) 1550 nm output power.

4. Summary and discussion

In conclusion, we have experimentally investigated the possibility of controlling the amplified spontaneous emission from Yb^{3+} ions in Er/Yb co-doped fiber amplifiers. We have presented and carefully analyzed a new method of suppressing the parasitic lasing and self-pulsing effects by creating a ring resonator for Yb-signal inside the Er/Yb amplifier. The results show, that the presence of a feedback loop allows to control the Yb-emission and stabilizes the amplifier operation at 1550 nm, making it more reliable. The presence of a well-defined and controlled 1064 nm signal increases also the power scalability, by minimizing the risk of active fiber damage (as a consequence of self-pulsing or even giant pulse formation). Another advantage of our method is its low-cost and simplicity. It does not require any additional seed laser or 1 μm band amplifier and utilizes only relatively cheap, commercially available fiber-optic elements (WDM couplers, isolators, etc.).

In order to confirm the effectiveness of our method, we have experimentally investigated another approach to suppress the Yb-ASE presented before [11,12] by utilizing an auxiliary seed signal in the Yb-band. Additionally, we have modified this method by launching the auxiliary signal not only co-directional to the 1550 nm, but also in the counter-directional scheme. The experiments have shown, that backward-seeding of an Er/Yb amplifier with a 1064 nm signal has a better influence on the 1550 nm signal. We have also investigated the dependence of the amplifier performance on the auxiliary signal power. The 1550 nm output power remains unchanged while changing the 1064 nm signal power in the range of 40–300 mW.

In our future work we will continue our investigation on Er/Yb fiber amplifiers stabilization by auxiliary Yb-band signals. Existing work has shown, that wavelength tuning of the 1 μm signal may have a big influence on the 1550 nm efficiency [12,13]. Another interesting area is further power scaling of the 1 μm input seed and investigating the amplifier behavior in the presence of much stronger signals (e.g. 1-2W).

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